Method And Apparatus For Measuring Particle Motion Optically

Cross-reference to Related Application

This application claims the benefits of and priority to U.S. Provisional Patent Application Serial No. 60/399,974 filed on July 31, 2002, the disclosures of which are incorporated herein by reference in their entirety.

Field of the Invention

The invention relates generally to the field of methods and apparatus for measuring particle motion, and more particularly to measuring particle motion using scattered light.

Background of the Invention

Quantitative information about a material in a region of space may be obtained remotely by observing how the material scatters radiation projected through that region. The scattering process normally causes the light to be reemitted diffusely in all directions though. Therefore, it is often difficult for a detection system to resolve the scattered light arising from one radiation source from the scattered light arising from another source.

One method that can be used to discriminate between scattering sources is to use radiation sources, for example, lasers, with different wavelengths. Then the scattered radiation can be divided into several beams, each beam falling on one of several detectors, each detector responding to only one wavelength. The primary problems associated with using different wavelengths are that multiple detectors and multiple lasers are used. The laser may have distinct properties, including power, size, emitting area, and/or emission patterns, which complicates calibration of the individual detectors, and compromises accuracy.

A technique for measuring particle velocity is Laser Doppler Velocimetry or Anemometry. Two coherent beams are projected at a small angle with respect to each other, and in the small region where they overlap, interference fringes form parallel to their mean direction. When a particle passes through this region, the amplitude of the scattered signal is modulated with a frequency that is equal to the speed divided by the fringe spacing. It is not possible to infer the velocity component (the speed component normal to the fringe pattern *including sign*) from this information without precisely shifting the frequency of one beam

relative to the other. In this case, the fringe pattern drifts toward one direction, and if the drift is faster than the largest speed in that direction, all the measurements of speed relative to the fringe motion will have the same sign. Adding the fringe velocity to the measured relative velocity produces the normal velocity including the correct sign.

While it is possible to use these instruments *in situ* with naturally occurring particles, it is not convenient. For example, since one requires coherence of the two beams, a slight change in the optical path associated with window degradation or a discontinuity in the medium can distort the fringe pattern. Furthermore, the naturally available particle distribution may not be suitable, for example, too many particles or the wrong size particle. Finally, since coherent beams require high quality lasers, the devices are relatively expensive.

Summary of the Invention

The present invention, in one embodiment, provides a method and apparatus for measuring particle motion using electromagnetic radiation. Beams of radiation are modulated with a distinct frequency and/or phase, and a particle traversing these beams scatters a portion of the radiation. Scattered radiation, which retains its modulation information, is then detected, and a cross-correlation technique is used to quantify the particle's motion, for example, particle velocity.

The invention uses adjacent spatial regions that are not optically resolved and, indeed, can even intersect. The invention utilizes all identical and inexpensive light sources, involves only a single detector, and is straightforward to generalize to higher dimensions. It does not involve coherent light and therefore is less susceptible to window degradation and isotropic scattering in the medium. The invention also shifts the complexity from relatively expensive optics, to relatively inexpensive electronics. The invention has the further advantage that under many situations, it can simultaneously provide detailed information about the particle size distribution, as well the particle velocity distribution, in a flow.

As used herein, the term "transparent medium" refers to a medium in which radiation can propagate a significant distance without being significantly absorbed or scattered by the medium. Such a medium is intended to include a vacuum through which a particle may move.

As used herein, the term "scatter" refers to all mechanisms by which radiation, incident from one direction, is re-emitted in a direction distinct from the first direction, with either the same or possibly a different wavelength. This includes, but is not limited to, reflection, refraction, diffraction, and fluorescence.

As used herein, the term "particle" refers to all non-uniformities that scatter radiation in a transparent medium. Particles may include, but are not limited to, sediment, bubbles, seed particles, density discontinuities, or any other material that locally scatters radiation. Particles are intended to include imperfections on a surface as well.

In one aspect, the present invention provides an apparatus for measuring particle motion. The apparatus includes a plurality of beams of radiation, each of the plurality of beams modulated at a respective, pre-determined frequency and a respective, pre-determined phase. The plurality of beams of radiation are directed at at least one particle. A detector is positioned to receive radiation scattered from each of the plurality of beams by the at least one particle. A processor is in electrical communication with the detector, and the processor cross-correlates radiation scattered from each of the plurality of beams by the at least one particle. The apparatus, in one embodiment, includes a phase sensitive detection circuit in electrical communication with the detector. In one embodiment, the radiation scattered includes a random component and a modulation frequency. The random component has characteristic frequencies lower than the modulation frequency of any of the plurality of beams.

In various embodiments, the plurality of beams of radiation form planes of radiation. In one embodiment, the plurality of beams of radiation includes two orthogonal beam pairs. In an alternative embodiment, the plurality of beams of radiation includes three orthogonal beam pairs. In another embodiment, the plurality of beams of radiation includes a plurality of non-orthogonal beam pairs.

In one embodiment, the separation of at least two of the plurality of beams of radiation is determined by a correlation distance of the particle. The separation may be between about 1 mm and about 1 cm. In one embodiment, a laser diode produces the plurality of beams of radiation. The wavelength, in one embodiment, is about 650 nm. In one embodiment, at least one of the plurality of beams of radiation is square wave modulated. In various embodiments, the modulation frequency is between about 20 kHz and

100 MHz, and is preferably between about 40 kHz and 100 kHz or between about 400 kHz and 800 kHz. In one embodiment, the modulation frequency of one of the plurality of beams is different than the modulation frequency of another of the plurality of beams. In various embodiments, the processor calculates particle velocity and/or particle size. In various embodiments, the pre-determined frequency of a first beam of the plurality of beams of radiation is substantially similar to the pre-determined frequency of a second beam of the plurality of beams of radiation, and the pre-determined phase of the first beam of the plurality of beams of radiation is substantially orthogonal to the pre-determined phase of the second beam of the plurality of beams of radiation.

In another aspect, the present invention provides a method of measuring motion of a particle. The method includes directing radiation from a plurality of beams at at least one particle, each of the plurality of beams modulated at a respective, pre-determined frequency and a respective, pre-determined phase. Radiation scattered by the at least one particle from two or more different beams is detected and cross-correlated to measure the motion of a particle. In various embodiments, the particle is located in a fluid. In one embodiment, the particle's velocity corresponds to velocity of the fluid.

Other aspects and advantages of the invention will become apparent from the following drawings, detailed description, and claims, all of which illustrate the principles of the invention, by way of example only.

Brief Description of the Drawings

The advantages of the invention described above, together with further advantages, may be better understood by referring to the following description taken in conjunction with the accompanying drawings. In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention.

Figure **1** is a schematic illustration of an embodiment of an apparatus for measuring particle motion according to the invention;

Figure **2A** is a top view of an exemplary embodiment of optics for shaping the beams of radiation of an apparatus for measuring particle motion according to the invention;

Figure **2B** is a side view of the embodiment of the apparatus for measuring particle motion shown in Figure **2A**;

Figure **3** is a top view of another exemplary embodiment of optics for shaping the beams of radiation of an apparatus for measuring particle motion according to the invention;

Figure **4** is a perspective view of an illustrative embodiment of two orthogonal beam pairs of an apparatus for measuring particle motion according to the invention;

Figure **5** is a perspective view of an illustrative embodiment of three orthogonal beam pairs of an apparatus for measuring particle motion according to the invention;

Figure **6** is a perspective view of an illustrative embodiment of three non-orthogonal beam pairs of an apparatus for measuring particle motion according to the invention;

Figure **7** is a plan view of an exemplary embodiment of collection optics for an apparatus for measuring particle motion according to the invention;

Figure **8** is a schematic illustration of a flow diagram showing the modulation, demodulation, and cross-correlating sequence, according to the invention; and

Figure **9** is a schematic illustration of an electronic circuit diagram capable of performing the work flow shown in Figure **8**.

Description of the Illustrative Embodiments

Figure **1** depicts an embodiment of an apparatus **10** for measuring particle motion. The apparatus **10**, in use, includes a first source of radiation **14**, a second source of radiation **18**, a first beam of radiation **22** generated by the first source of radiation **14**, a second beam of radiation **26** generated by the second source of radiation **18**, an observation region **30** in which particles scatter radiation, a first beam of scattered radiation **34**, a second beam of scattered radiation **38**, and a detector **42**. The two sources **14** and **18** project the two beams of radiation **22** and **26**, respectively, in a first direction through a transparent medium. The two beams **22** and **26** are intersected by a particle (not shown) traveling in a second direction. As the particle crosses the first beam of radiation **22** in the observation region **30**, it scatters radiation and forms the first beam of scattered radiation **34**, which is received by the detector **42**. As the particle crosses the second beam of radiation **26** in the observation region **30**, it scatters radiation and forms the second beam of scattered radiation **38**, which is received by the detector **42**. The observation region **30** is defined by the beams of radiation **22** and **26** and the field of the detector **42**, which will be described in more detail below.

The sources of radiation **14** and **18** may be coherent or incoherent. The sources of radiation **14** and **18** may be, for example, laser diodes, light emitting diodes, or sources that

generate non-optical electromagnetic radiation, such as microwaves. In one embodiment, the radiation is not electromagnetic, but is, for example, acoustic. Acoustic waves propagate further in most transparent media and are most sensitive to scattering by larger particles, but because their characteristic wavelengths are much longer than, for example, optical wavelengths, acoustic waves are inherently of lower resolution. Electromagnetic radiation typically is less penetrating and produces a more local probe of the motion of a particle. Electromagnetic radiation resolution can be much greater than acoustic waves, however, and because of the shorter wavelength of the electromagnetic waves, smaller particles scatter them more efficiently. Electromagnetic radiation is also preferred when there are no naturally occurring particles large enough to scatter acoustic waves.

In one embodiment of the apparatus **10**, the sources of radiation **14** and **18** are laser diodes with a wavelength of about 650 nm and a power of about 12 mW. In this embodiment, the apparatus **10** is adjusted so that the observation region **30** is at a distance of between about 30 cm and about 2 m from the sources **14** and **18**. The beams of radiation **22** and **26** may be parallel or substantially parallel.

To make quantitative measurements, such as particle velocity or particle size, each beam of radiation **22** and **26** is modulated with a pre-determined frequency and a pre-determined phase. The sources of radiation **14** and **18** may be internally modulated using, for example, an electronic circuit or computer software, or the beams of radiation **22** and **26** may be externally, mechanically modulated using, for example, a mechanical chopper or acousto-optic modulator.

As described above, the response of the particle to the beams of radiation **22** and **26** is to scatter a time-dependent fraction, $f_K(t)$ of the incident radiation, where K represents an individual beam of radiation, such as **22** or **26**. Because each beam of radiation **22** and **26** is amplitude modulated by a unique high-frequency function of time, $\phi_K(t)$, the scattered radiation **34** and **38** is then modulated with the same function $\phi_K(t)$ as its respective "source" beam of radiation **22** and **26**. Since the individual beams of radiation **22** and **26** are necessarily incoherent, the total scattered signal from the active region **30** is the sum of the scattering intensities arising from the individual beams **22** and **26**. The intensity of the signal on the detector **42** coming from the light scattered from the observation region **30** is:

$$I(t) = \sum_K f_K(t)\phi_K(t) \qquad (1)$$

Because the frequency of the modulation and the phase of the modulation are known, phase sensitive detection or "lock-in" detection, which will be described in more detail below, may be used to extract the various $f_K(t)$ that are superimposed on the detector **42**.

The beams of radiation **22** and **26** may be sinusoidal wave modulated or square wave modulated. The frequency of the modulation may be between about 20 kHz and about 100 MHz, although a lower or higher modulation frequency may be desirable depending on the application. In one embodiment, the modulation frequency is between about 40 kHz and about 100 kHz. In another embodiment, the modulation frequency is between about 400 and about 800 kHz.

In various embodiments, the beams of radiation **22** and **26** are produced by a single source. In one such embodiment, the frequency of modulation is the same for the two beams of radiation **22** and **26**, but the two beams of radiation **22** and **26** may have different phases. Preferably, the phases of the two beams **22** and **26** are orthogonal, or $\pi/2$ out-of-phase.

The velocity component, V_x of the particle normal to the two beams of radiation **22** and **26** is:

$$V_X = d / \Delta t, \qquad (2)$$

where d is the separation between the two beams of radiation **22** and **26**, and Δt is the time that the particle takes to travel between the two beams of radiation **22** and **26**. Typical separation between the beams of radiation **22** and **26** is between about 1 mm and about 1 cm, although a smaller or larger separation may be desirable depending on the application. The separation of the two beams **22** and **26** may be determined by the correlation distance of a particle, or that distance over which the particle's velocity is substantially unchanged. At a separation beyond the correlation distance, a meaningful V_x can no longer be derived.

Many particles of varying sizes pass through the observation region **30** during a measurement. Since their sizes, concentration, and arrival times are random, their signals are as well. Since most particles that cross the first beam of radiation **22** cross the second beam of radiation **26** at a time $\Delta t = d / V_X$ later, the signal scattered by the first beam at time t, $f_1(t)$, is similar to the signal scattered by the second beam, $f_2(t)$, at a time Δt later. Therefore, the two scattered signals are strongly correlated.

The mathematical method that can be used to extract Δt is cross-correlation. One calculates the integral:

$$H(\tau) = \int_{-\infty}^{\infty} f_1^*(t) f_2(t+\tau) dt \qquad (3)$$

where, if $f_2(t)$ is partially comprised of pulses which are delayed relative to those in $f_1(t)$ by an amount Δt, the function $H(\tau)$ will have a maximum when $\tau = \Delta t$. Therefore, knowledge of the separation of the beams, *d*, together with the cross-correlation function maximum, Δt, permits one to calculate the velocity component V_x normal to the beams of radiation **22** and **26**. The cross-correlation function $H(\tau)$ may be calculated numerically if the functions are known in digital form over some time period that is long in comparison to Δt, which may be either positive or negative. Therefore, the measurement directly provides the velocity including the correct sign, which corresponds to the direction the particle is traveling and is used to interpret measurements made in more than one dimension.

If the velocity is not constant over the period for which the correlation function is computed, Δt corresponds to an average value of the time delay over that period. If the velocity is variable on the time scale of Δt, it is advantageous to decrease the beam separation, which decreases Δt as well. The resolution of the experiment also decreases, though, so there is a trade-off between the resolution and the response time. Particle size often may be directly extracted from the intensity of the demodulated scattered signal pulses. Using cross-correlation to determine the velocity permits one to calculate the number of particles of a particular size per unit volume.

Figures **2A** and **2B** show an exemplary embodiment of an apparatus **10'** for measuring particle motion, including optics for shaping the beams of radiation **22** and **26**. The radiation sources **14** and **18** may include lenses, apertures, and other optics to align the beams of radiation **22** and **26**, for example to produce two substantially parallel light beams. According to the embodiment illustrated in Figure **2A**, four prisms **46** bring the beams **22** and **26** close to and nearly parallel to each other, while a first cylindrical lens **50** and a second cylindrical lens **54** form the two beams of radiation **22** and **26** into planes of radiation, for example, ribbons or sheets, by expanding the beams **22** and **26** in one plane. Figure **2B** depicts a side view of the apparatus **10'**, thus only the first beam of radiation **22** is shown as a

plane. The combination of the four prisms **46** and the two cylindrical lenses **50** and **54** control the spacing between the two beams **22** and **26**.

In one embodiment, the four prisms **46** are right angle prisms. The prisms **46** may be oriented slightly non-perpendicular to the incoming beams **22** and **26**, so that light reflected from the first surfaces **58** does not reflect directly back into the sources of radiation **14** and **18**. The prisms **46** may include a reflective coating on the hypotenuse face. The two beams of radiation **22** and **26** are converted into planes of radiation by passing them through the two cylindrical lenses **50** and **54**, which are separated by the sum of their focal lengths. A typical focal length for the first cylindrical lens **50** is between about 0.5 cm and about 1 cm. A typical focal length for the second cylindrical lens 54 is between about 1 cm and about 5 cm. By careful orientation of the axes of the sources 14 and 18 and adjustment of the cylindrical lenses **50** and **54**, the beams of radiation **22** and **26** are preferably shaped to a vertical height of about 8 mm and a thickness of about 0.1 mm.

Figures 3 shows another exemplary embodiment of an apparatus **10″**, where the four prisms **46** are replaced by a single equilateral prism **62**. The beams enter and exit the prism substantially normal to its faces, and are deflected by total internal reflection. By translating the prism **62** along an axis parallel to the beams of radiation **22** and **26** (see arrow **66**), the separation of the two beams may be adjusted. The cylindrical lenses **50** and **54** convert the beams of radiation **22** and **26** into planes of radiation.

The apparatus **10**, **10'**, and **10″** shown in Figures **1-3** ideally measure velocity in a single dimension by use of a single beam pair, for example, the two beams of radiation **22** and **26**. Generalization to either two- or three-dimensions may be performed by projecting additional beam pairs through the active region **30**. Figure **4** depicts an illustrative embodiment of two beam pairs **70** capable of making a measurement in two-dimensions. The first beam pair **72** including the two beams of radiation **22** and **26** is intersected by a second beam pair **72′** including a third beam of radiation **22′** and a fourth beam of radiation **26′**. According to the illustrative embodiment, the two beam pairs are orthogonal, although they need not be. Each beam **22**, **22′**, **26**, and **26′** is "labeled" with a unique frequency and phase, and the two velocity components, V_X, V_Y normal to each beam pair are derived using the method described above. Because the values of V_X and V_Y including the sign are derived, the velocity in two or more dimensions may be unambiguously determined.

Figure **5** shows an illustrative embodiment of three beam pairs **74** capable of making a measurement in three-dimensions. The first beam pair **72** including the two beams of radiation **22** and **26** and the second beam pair **72′** including the two beams of radiation **22′** and **26′** are intersected in the active region **30** by a third beam pair **72″** including a fifth beam of radiation **22″** and a sixth beam of radiation **26″**. According to the illustrative embodiment, the three beam pairs are orthogonal, although they need not be. As described above, each beam of radiation **22**, **22′**, **22″**, **26**, **26′**, and **26″** is "labeled" with a unique frequency and phase, and the three velocity components, V_X, V_Y, V_Z normal to each beam pair can be derived.

If a particle traverses a beam pair with a small angle with respect to the plane of a given beam pair and the beam pair spacing is significant, the particle may cross one beam, but not cross the adjacent beam. Figure **6** depicts an illustrative embodiment of three beam pairs **78**, with non-orthogonal orientation for making a measurement in two-dimensions. This embodiment achieves higher directional resolution perpendicular to the beam axis **82** by using only the two beam pairs that give the smallest Δt (or the best defined cross-correlation peaks) to define the velocity component V_X, V_Y. For example, if a particle enters the three beam pairs **78**, substantially in plane with the first beam pair **72**, then the particle may not cross one of the beams of radiation **22** and **26**. The particle will cross both beams of the second beam pair **72′** and the third beam pair **72″**, making a measurement of the particle motion possible. Alternatively, if the particle enters the first beam pair **72** at a very small angle with respect to the plane of the first beam pair **72**, the particle may cross a first beam of radiation **22**, cross the second beam pair **72′**, cross the third beam pair **72″**, and then finally cross the second beam of radiation **26**. In this instance, the signals from the second and third beam pairs **72′** and **72″** are used to calculate particle motion, and the signal from the first beam pair **72** is disregarded.

Referring back to Figure **1**, a suitable detector **42** may be, but is not limited to, a photomultiplier tube (PMT) or a photo diode, such as an avalanche photo diode. In an alternative embodiment, a series of detectors **42** may be used to detect the radiation scattered **34** and **38** by the particle. The detector **42** may also include a set of optics for directing the radiation scattered **34** and **38** onto the detector **42**.

Figure **7** shows an embodiment of a detector **42'** including a pair of colored glass filters **86**, an "inverse" iris **90**, a window **94**, an interference filter **98**, a doublet lens **102**, a meniscus lens **106**, a right angle prism **110**, an aperture **112**, a PMT **114**, and a housing **118**. While in the transparent medium, the scattered radiation **34**, **38** passes through the pair of colored glass filters **86**, which perform an initial narrow band selection. The bandwidth of the colored glass filter pair **86** is between about 50 nm and about 200 nm. The "inverse" iris **90**, which is in the form of a narrow annular region, reduces the amount of radiation transmitted to the PMT **114** by restricting the radiation to only the edge regions of the housing **118**. The "inverse" iris **94** also reduces the depth of field, rather than increase it like a conventional iris.

The scattered radiation **34**, **38** next passes through the window **94** and enters the housing **118**. The narrowband, for example about 10 nm, interference filter **98** passes the laser wavelength, but eliminates almost all of the ambient light that may otherwise saturate the detector. Remaining background light is typically not modulated, and therefore does not contribute to any of the scattered radiation **34**, **38** signals. It does however reduce the dynamic range of the detector available for true signals and adds to the random detector noise. The doublet lens **102** and the meniscus lens **106** focus the scattered radiation **34**, **38** onto a small, circular aperture **112** that, together with the beam geometry, defines the boundaries of the observed scattering region **30**. Typical aperture **112** size is between about 1 mm and about 5 mm, and preferably the aperture **112** size is between about 2 mm and about 3 mm. For example, an aperture **112** of about 2 mm diameter at the lens focal plane corresponds to an observed region **30** of about 1 cm diameter, when the lens magnification is 0.2. Scattered radiation **34**, **38** reflected by the right angle prism **110** and passing through the aperture **112** is incident on the PMT **114**, which produces an electrical signal that is subsequently processed to extract the velocity component(s).

As described above, the scattered light intensity signals from each source K, $f_K(t)$, multiplied by the corresponding modulation functions $\phi_K(t)$, are collectively incident on the detector, which produces an electrical output proportional to their sum. To extract these functions $f_K(t)$ separately from the detector output, the detector signal is passed through a phase sensitive detection circuit. In one embodiment, the circuit is a multi-channel device that has a separate channel for scattered radiation corresponding to each source, K.

Alternatively, the circuit includes a separate phase sensitive detector (PSD) for each beam of scattered radiation corresponding to each beam of radiation.

In either embodiment, the output of each PSD channel, after filtering to remove the modulation and beat frequencies, is proportional to the scattered signal associated with a single source *K*. The resulting signals from these K channels are now cross-correlated in pairs, and from these correlations the velocity components may be calculated.

Figure **8** depicts an exemplary embodiment of a flow diagram for modulating the beams of radiation **22** and **26** and demodulating and cross-correlating the scattered radiation **34** and **38** to extract quantitative information regarding particle motion. The flow diagram is for a single beam pair for measuring one velocity component, although the modulation/demodulation may be extended to two or three dimensions by modulating/demodulating additional beams of radiation in a similar fashion. The steps need not be performed in the order described to successfully measure particle motion. The work flow described below may be realized with, for example, an electronic circuit or computer software.

According to the illustrative embodiment, a modulation frequency is generated (step **122**) and directed to drivers for the sources of radiation (step **124**). A time-delayed reference frequency is also generated (step **126**). The modulation frequency and the reference frequency have the same frequency, but the phase of the reference frequency is shifted to compensate for the delay for the scattered radiation to reach the detector and to compensate for the rise time of the detector and/or a preamplifier. In addition, in an embodiment utilizing a plurality of laser diodes , the reference frequency for each laser diode may be shifted independently to account for variations in the rise time of each laser diode.

Modulated radiation is scattered by a particle traversing the beams of radiation in the observation region (step **128**), and the scattered radiation is collected by the detector (step **130**). The signal from the detector may be treated with a pre-amplifier. The reference frequency is directed to a set of PSD's, which extract a signal for each source of scattered radiation (step **134**). The output from the PSD's may be filtered by a low-pass filter and/or notch filters to remove low frequency components of the signal. The scattered radiation, each scattered beam originating from the particle crossing the individual beams of radiation,

is then cross-correlated (step **138**), and a calculation of, for example, particle velocity or particle size is performed using a processor(step **142**).

Figure **9** shows an illustrative embodiment of an electronic circuit for performing the method shown in Figure **8**. The circuit is constructed primarily from CMOS logic chips. DC power **150** is applied to a crystal clock chip **154** running at 4 MHz, which provides the timing, and a reset function **158** is generated by a Schmitt Trigger circuit. The clock **154** drives two divider sequences **162** (÷100) and **166** (÷ 80), to generate two square wave digital logic signals running at 40 kHz and 50 kHz, respectively. These digital logic signals control electronic SPDT switches **170** and **174** that provide the modulation voltage required by the laser driver circuits **178** and **182**. Thus, the outputs of laser diodes **186** and **192** are modulated with approximately square waveforms, the first **186** at 40 kHz and the second **192** at 50 kHz. The digital logic signals from the two divider sequences **158** and **162** are also inputted into phase shifting circuits **196** and **200** to provide reference square waves to PSD circuits **204** and **208**.

The detector section **42″** includes a PMT **114** driven by a battery operated, high voltage power supply **212**. The output of the PMT **114** feeds a transimpedance amplifier **216** including an operational amplifier chip. The time constant of the circuit may be less than 0.1 μs. Thus, the output of the amplifier primarily includes resolvable photon derived pulses until the PMT approaches saturation. The output of the preamplifier **216** feeds an automatic gain control circuit **220** that reduces the PMT voltage whenever the signal gets large enough to saturate the PMT **114**. In normal operation, the PMT voltage is held relatively low, for example, about 500 V, which reduces the gain significantly. Increasing the intensity of scattered radiation incident on the PMT **114** by opening up the iris **90**, for example, shown in Figure **7**, can compensate for this, since the scattered radiation available is typically overabundant. The advantage of this mode of operation is that, since the PMT **114** has a maximum current rating, operating at a lower gain and higher light intensity increases the number of pulses. Since the source of noise is shot noise on these pulses, the signal to noise ratio is increased. The preamplifier **216** also drives a balanced pair of op-amps configured as a follower **224**/inverter **228** pair. Their time constant is typically about 0.1 μs.

Phase sensitive detection is accomplished by switching between the direct and inverted signals by using electronic SPDT switches **204** and **208** driven by the digital

reference signals from the switches' respective phase shifting circuits **196** and **200**. Two channels, each corresponding to one of the modulation/reference frequencies are operated in parallel, with both being driven by the same follower **224**/inverter **228** pair. Following phase sensitive detection, the signals pass through 10 kHz active notch filters **232** and **236**, which removes the beat frequency between channels. For example, for modulation frequencies of 40 kHz and 50 kHz, the beat frequency is the difference between the two modulation frequencies. The signals then pass through low pass filter amplifiers **240** and **244**, and the signals are digitized by A/D digital acquisition cards **248** and **252** for analysis by a computer. The final low pass filter time constants are chosen to insure that there is no aliasing in the subsequent A/D conversion step.

There are numerous applications in which it is desirable to measure the velocity of particle motion, particularly when the particles are contained in a transparent medium that is moving. If the particles are small enough, they will be entrained with the medium and a measurement of their velocity becomes equivalent to a measurement of the velocity of the medium itself. In many cases, the particles are naturally present, but in other cases it is necessary and desirable to seed the medium with probe particles whose properties are better defined. There are many situations, particularly in the measurement of the motion of fluids outside of the laboratory, such as flow of streams and seawater, the atmosphere, fluids in pipelines, for example, oil or natural gas, where seeding is impractical. In such instances, naturally occurring particles, such as sediment or air bubbles, are used.

In an embodiment where sediment is measured in seawater, a submersible unit is constructed that houses the sources of radiation and the detector assembly. Cables may be used to connect the submersible unit to the surface of the seawater. Preferably, the electronic circuit is used and is located in close proximity to the sources and detector. In such an embodiment, the observation region is located in the seawater about 300 mm beyond the final window of the submersible unit. The visible portion of the beams is about 20 mm long, and over this distance, the beams are essentially parallel, separated by about 2mm, and of an approximately constant cross-section of about 0.2mm x 8mm. The light from the sources is highly polarized along the axis normal to the plane of the beams. This optimizes the amount of light reflected by the final prism, and insures that there is a high degree of polarization perpendicular to the optical axis of the detector.

While the invention has been particularly shown and described with reference to specific illustrative embodiments, it should be understood that various changes in form and detail may be made without departing from the spirit and scope of the invention as defined by the appended claims.